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RADIOLOGICAL RISK CURVES FOR THE LIQUID RADIOACTIVE WASTE TRANSFER FROM ANGRA 1 TO ANGRA 2 NUCLEAR POWER PLANTS BY A CONTAINER TANK

A. S. M. Alves[1], E. M. dos Passos[1], J. P. Duarte[2] and P. F. Frutuoso e Melo[3]

[1] Eletrobrás Termonuclear S.A. - ELETRONUCLEAR
Rua da Candelária, 65 – 7º andar
20091-906 Rio de Janeiro, RJ
asergi@eletronuclear.gov.br, epassos@eletronuclear.gov.br

[2] Escola Politécnica, Departamento de Engenharia Nuclear
Universidade Federal do Rio de Janeiro
Av. Horácio Macedo 2030, Bloco G, Sala 206, Cidade Universitária
21941-914 Rio de Janeiro, RJ
julianapduarte@poli.ufrj.br

[3] COPPE – Programa de Engenharia Nuclear
Universidade Federal do Rio de Janeiro
Av. Horácio Macedo 2030, Bloco G, Sala 206, Cidade Universitária
21941-914 Rio de Janeiro, RJ
frutuoso@nuclear.ufrj.br

ABSTRACT

Eletrobras Termonuclear has a radiowaste management program focused on reducing the produced volumes, for which it has considered to transfer Angra 1 liquid radioactive waste by a container tank to be processed and packed in Angra 2. This paper presents a radiological risk study for providing the necessary technical foundations to obtain the license from the regulatory agency for implementing this transfer operation. Out of the 92 accident scenarios identified with the help of a preliminary hazard analysis, the greatest risk of fatal cancer for members of the public was equal to 6.9×10^{-13} fatalities/yr, which refers to the accident scenario involving intrinsic failures of valves, hoses, flanges, seals, gaskets and instrumentation lines, while filling the container tank at Angra 1 filling station. This risk figure is about ten million times less than the one adopted by Eletronucler for such a waste transfer. The highest frequency was also associated with this type of scenario, and its value was equal to 1.4×10^{-6} yr^{-1}. This paper also presents and discusses the radiological risk curves for the three possible in-plant transfer routes, the Angra 1 filling station and Angra 2 discharging station and the overall risk curve in order to allow for a broader perspective of the results obtained. These risk curves display the accident scenarios frequencies against radiation doses by considering relevant in-plant and surroundings release paths. In these curves, the extreme scenarios mentioned earlier can be clearly identified in terms of occurrence frequencies and radiation doses.

1. INTRODUCTION

Eletrobras Termonuclear (ETN), the Brazilian nuclear utility, has created a study group to consider the radioactive waste management of Angra nuclear power facility. Established in 2003, this group has worked to meet the goal of an ETN's strategic plan: "To implement a waste management program focused on reducing the waste volume produced and its initial storage." For this purpose, all radioactive waste produced in Angra 1 and Angra 2 nuclear power plants today and Angra 3 in the near future are the subject of technical and administrative measures, aimed at further reduction of its volume within the established radiological and safety limits [1].

To reduce the amount of concentrated packed waste of Angra 1 nuclear power plant evaporator, ETN has considered it more appropriate to implement improvements in the liquid waste treatment system and to transfer the liquid waste of Angra 1, by container tank, to be processed and packed in Angra 2 nuclear power plant. The container tank is basically a shipping container 6,058 mm long, 2,500 mm wide, and 2,438 mm high with a steel tank of inner volume equal to 10 m^3. It is equipped with some systems as electric power, compressed air, filling and emptying, venting, instrumentation and control. The steel tank is manufactured with 55 mm thickness representing a good protection against external missiles and internal radiation sources (radiation shielding).

We developed the safety and risk analysis for this transfer operation in order to fulfill requirements from the National Commission of Nuclear Energy (CNEN). One of the requirements was to make a point estimate of the radiological risk due to accidental scenarios during the transfer operation. This radiological risk point estimate was presented at the European Safety and Reliability Conference held in Helsinki, Finland [2]. The analysis took into account radiological accidents with radioactive material release during the transfer operation of liquid waste involving ionizing radiation. Scenarios covered (events, models and parameters) related to the transfer of the waste by container tank in the inner area of the Angra nuclear power plant site, covering all phases of the liquid radioactive waste transfer. Non-radiological risks due to construction or improvement implementation in existing facilities in the site were not covered, even those preparatory for plant operation, for example, the radiological risk of temporary workers. Further details of our analysis can be found in [3].

2. TRANSFER OPERATION OF THE LIQUID RADIOACTIVE WASTE

The transfer of liquid radioactive waste stored in the waste tank located internally in Angra 1 will be performed in a transfer area of Angra 1 already specified, by the use of a container tank, specified route transfers, and also the liquid radioactive waste transfer area of Angra 2. The container tank displacement will be restricted to the protected area between Angra 1 nuclear auxiliary building and Angra 2 auxiliary reactor building. After processing the waste liquid in Angra 2 by means of a segregated evaporator, the concentrate obtained from this operation will be transferred to one of three Angra 2 concentrate tanks (dedicated tanks), available to segregate waste from Angra 1. After filling of the tank or by a decision in advance of the operation staff, this concentrate will be embedded in bitumen, as is regularly done in Angra 2 with the concentrate coming from this plant.

3. PROPERTIES OF THE LIQUID RADIOACTIVE WASTE

The material to be transferred by the container tank basically comprises liquid radioactive waste in the form of a water solution with some substances diluted in it. This solution is characterized according to its physical, chemical as well as other properties that may cause damage to human beings, facilities and the environment.

For the liquid radioactive waste to be properly characterized from the point of view of safety and risk analyses, information about its composition, physical, chemical and toxicological properties have been gathered. The typical composition of the liquid radioactive waste to be transported by the container tank is shown in Table 1 [2].

Table 1: Typical Liquid Radioactive Waste Composition [3]

Constituent	Concentration (ppm)
Silica	6.0
Sodium	47
Chloride	96
Magnesium	0.65
Boron	261
Calcium	28
Aluminium	< 0.010
Sulphate	116,000
Nitrate	665
Nitrite	< 1
Phosphate	20,500
Potassium	< 0.010
Suspended solids	250
Solids, total	0.12 %

The radioactive waste liquid is a solution composed by water and the chemicals listed in Table 1. It is observed that water is the dominant substance (its mass is approximately 99% of the solution mass). The physical and chemical properties of the liquid radioactive waste are presented in Table 2 [3].

The main toxicity of the radioactive waste liquid to be transferred from Angra 1 to Angra 2 refers to its radioactivity. From the point of view of safety and risk analysis, it is sufficient to consider the radiation as composed by α and β particles, and γ rays (photons).

Table 2: Physical and Chemical Properties of the Liquid Radioactive Waste [3]

Physical and Chemical Properties	Unity	Value
Solid fraction	[%]	0.12
Soluble fraction	[ppm]	250
Boiling point	[^{o}C]	100
Density	[kg/m^3]	1400

The main radionuclides present in the liquid radioactive waste, along with their activity concentrations are presented in Figure 1 [3]. It is clear from this figure that the most important radionuclides, in terms of activity concentration, from the 19 displayed, are ^{3}H, ^{134}Cs, ^{136}Cs, ^{137}Cs and ^{58}Co.

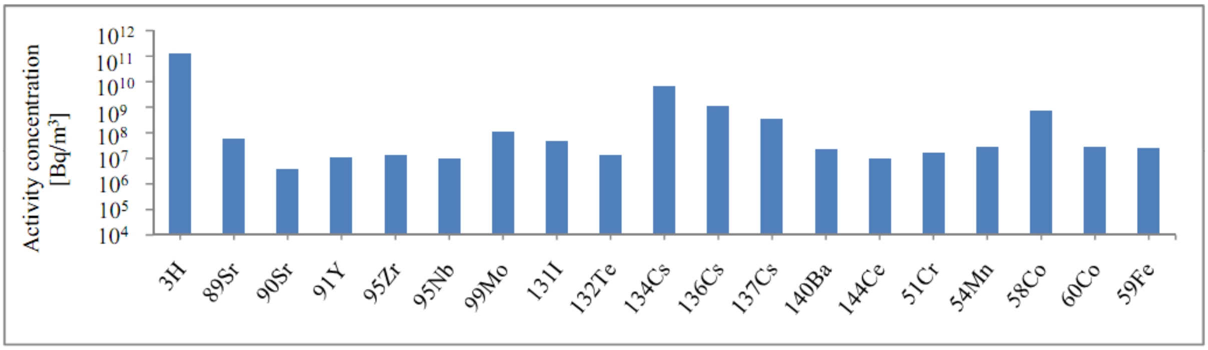


Figure 1: Liquid Radioactive Waste Activity Concentration by Radionuclide [3]

4. SAFETY AND RISK ANALYSES

The purpose of the safety and risk analyses is to demonstrate that the proposed transfer of liquid waste from Angra 1 to Angra 2 by a container tank meets the National Commission of Nuclear Energy's regulatory requirements. Thus, the study performed shows that the radiation dose and the risks are within acceptable values. Normal operating conditions and incident and/or accidents for this transfer operation have been considered in the analysis. The interpretation of the words 'incident' and 'accident' is that of the International Atomic Energy Agency's glossary [4].

The safety and risk analyses have focused on the radiological safety of all operation phases of waste transfer and have provided subsidies for the development of potential operational improvements. The most critical phases of the transfer operation have been identified.

An estimate of radiological doses received by workers during a normal liquid radioactive waste transfer from Angra 1 to Angra 2 via container tank is fundamental to an assessment of the transfer operation safety. Low doses in comparison with the individual dose limits for workers in radioactive areas indicate that this operation can be safely performed, using few employees [5].

On the other hand, high doses indicate that this transfer operation must be reviewed and perhaps that is necessary to add new design items, such as additional radiological shields, the need for remote working and/or other engineering solutions.

The collective radiation dose can be conservatively estimated for the normal operation of liquid radioactive waste transfer from Angra 1 to Angra 2 by a container tank. The estimated collective doses are reproduced in Figure 2 [6]. It can be observed that the collective dose estimated for a complete liquid radioactive waste transfer from Angra 1 to Angra 2 is equal to 275.1 person-μSv. It is observed that this dose is very low as compared to the annual dose limit of 20 mSv for a worker [5]. It is also observed that the most significant collective doses are related to the container tank filling in Angra 1 transfer area (***C***), hose disconnection, line cleanup, radiometry and decontamination (***D***) and also the container tank emptying in Angra 2 transfer area (***G***).

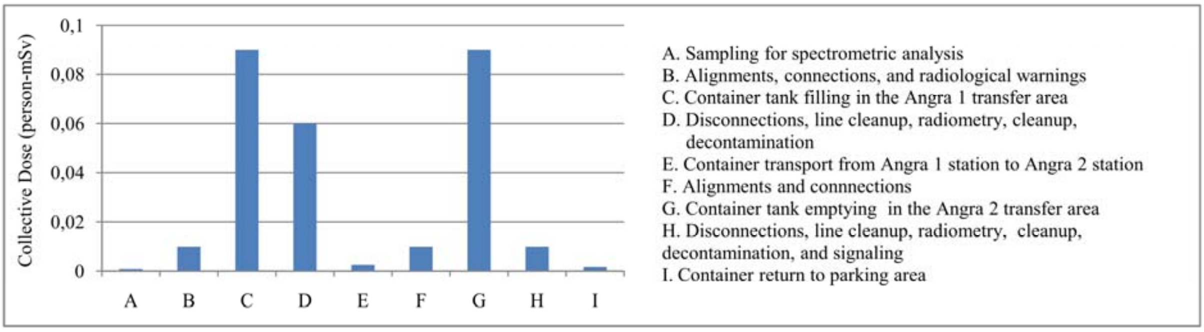


Figure 2: Collective Doses for a Full Liquid Radioactive Waste Transfer from Angra 1 to Angra 2 [6]

Although the operation planning related to the waste transfer has been developed to allow an excellent performance, both from the intended use and safety standpoints, conditions of hypothetical incident and/or accident are previewed and analyzed for the installation.

The behavior of the installation involved in the waste transfer for the case of incidents and/or accidents gives an idea of its radiation safety. The radiation safety is closely related to the risk involved, i.e., lower risk indicates better safety.

The radiological risk is directly proportional to the frequency of occurrence of a radionuclide release from the container tank and to the radiological impact associated with this release. Generally, this frequency is a function of *a*) various systems and components present in the container tank; *b*) their design and construction characteristics; *c*) loading and unloading stations; *d*) engineering barriers designed for the installation; *e*) natural barriers existing in the site provided for transfer operations; and *f*) and man's interaction with it.

The frequency of radionuclide accidental release is also reduced in this transfer operation due to the use of a container tank specially designed for this operation with liquid waste. The steel wall of the transfer tank (mounted inside the container) represents an important engineering barrier that hinders radionuclide release in case of radiological accidents.

The safety and risk analyses comprise the following steps: *a*) development of a Preliminary Hazard Analysis (PHA) containing the incident and/or accident scenarios postulated for the transfer operation of radioactive liquid waste from Angra 1 to Angra 2 by a container tank; *b*) selection of the most important accident scenarios; *c*) determination of accident scenario frequencies; *d*) calculation of radiation dose in case of accidents; *e*) effect calculations (casualties due to ionizing radiation exposure); *f*) estimation of radiological risk.

PHA is a structured technique that has been developed by the U.S. Army [7]. It aims to identify the hazards present in a facility, which may be caused by undesired events. It can be used in installations in the early stage of development, design stages or even in units already in operation, allowing, in this case, conducting a review of existing safety features. PHA focuses on all hazardous events whose failures originate at the facility under analysis, including intrinsic equipment, instrumentation and materials failures, as well as human errors. PHA identifies the hazards, causes, effects (consequences) and the corresponding severity categories. Observations and recommendations pertaining to the identified hazards are included, and the results are presented in a standardized worksheet. Details on this analysis may be found in [2]. It is important to stress that these initial 92 scenarios have been identified by means of an exhaustive discussion of possible danger to the transfer operation at the plant site. Table 3 displays the worksheet we have used to develop the preliminary hazard analysis.

Table 3: Worksheet used for the Preliminary Hazard Analysis

Preliminary Hazard Analysis (PHA)								
System:		Module:					Date:	Page
Hazard	Cause(s)	Detection Mode(s)	Effect(s)	Frequency Category	Severity Category	Risk Category	Recommendations	Scenario Number

Table 4 presents the adopted classification of the identified scenarios according to their frequency of occurrence [8]. This classification has typically been used in preliminary hazard analyses in Angra nuclear power facility.

Table 4: Accidental Scenarios Classification by Frequency of Occurrence [8]

E	**D**	**C**	**B**	**A**
Unlikely	Virtually unlikely	Highly Unlikely	Likely	Occasional
Not expected to occur during plant useful life	Chances of occurrence during plant useful life	Unlikely during plant useful life	Expected to occur at most once during plant useful life	Expected to occur at least once during plant useful life

10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} f(/yr)

Table 5 presents the adopted classification of the identified scenarios according to their severity [8]. This severity classification has been used in conjunction with the frequency classification shown in Table 4.

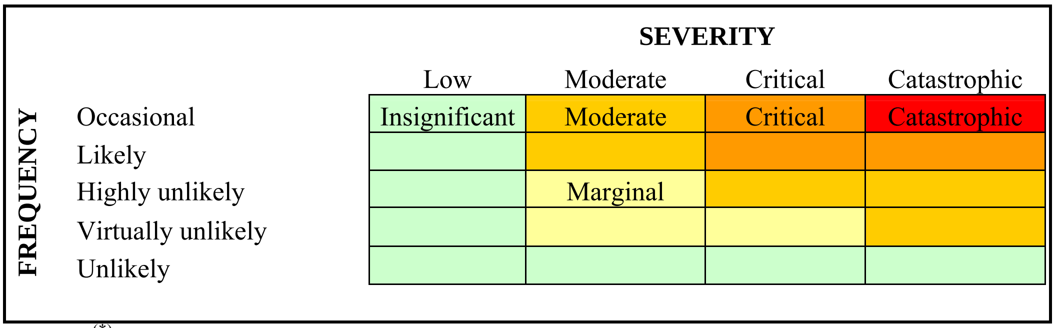
The possible use of Hazard and Operability Studies (HAZOP) [6] has been discarded because the focus was on hazards and not deviations from normal operation, although these latter may be viewed as a subset of the former.

With the information in the worksheets it is possible to semi-quantitatively estimate the risks for each of the postulated accident scenarios, using risk matrices such as the one shown in Figure 3, where the classification in the colored boxes refers to the used risk categories [8].

Table 5: Accidental Scenarios Classification by Severity [8]

Classification	Label	Description
I	Catastrophic	Irreparable damage to equipment, property and/or the environment, leading to unit and/or system disorderly shutdown (slow or impossible repair); causes death or serious injury to several people (employees and/or member of the public).
II	Critical	Severe damage to equipment, property and/or the environment, leading to unit and/or system ordered shutdown; lesions of moderate severity in employees and/or members of the public (remote probability of death of employees and/or third parties); requires immediate corrective action to prevent becoming an accident.
III	Marginal/Moderate	Light damage to equipment, property and/or environment (damages are controllable and/or with low repair costs); minor lesions to workers, outsourced personnel or people outside unit.
IV	Low or Insignificant	No damage or minor damage to equipment, property and/or the environment; injuries and/or deaths of employees, third party and/or members of the public do not occur; cases of first aid or minor medical treatment at most.

Figure 3: Risk Matrix Used for Classifying the Accident Scenarios (*) [8]



(*) The classification in the colored boxes refers to the different risk categories

For the case of the safety and risk analyses of the liquid radioactive waste transfer from Angra 1 to Angra 2 by a container tank, the most important accident scenarios have been selected (using the results of the preliminary hazard analysis) according to the following scenario selection criteria: *a*) severity equal to or higher than moderate (including moderate, critical and catastrophic); *b*) risk equal to or higher than marginal (including marginal, moderate, critical and catastrophic).

These criteria have been used to discriminate a smaller group of accident scenarios from those initially identified by the preliminary hazard analysis, which will be studied in detail by using more appropriated mathematical models. Typically, less than half of the identified accident scenarios are analyzed in detail because those with less significant contributions both from the point of view of risk and severity are discarded [2].

The frequencies of the accident scenarios identified after use of the criteria presented in the two mentioned items were determined as discussed below. In general, the calculation involves the use of the frequency of some event that is not a failure (for example, the yearly transfer of waste, which is defined by plant operating conditions) and probabilities associated with it, which refer to the occurrence of failures or events that can lead to failures (e.g., leakage through a flange, fragment or shock wave from the explosion of an H_2 cylinder).

The accident scenarios for which frequencies have been calculated can be roughly classified into: scenarios involving equipment failures (e.g., flange and gasket leaking, rupture of valve disc, etc.), scenarios involving human failures (operator leaves valve open, etc.) and accident scenarios involving external events (e.g., associated with the explosion of H_2 cylinders).

These frequencies are usually estimated from the analysis of operation logs similar to those considered here, since this transfer has never been performed in Angra site. The probabilities mentioned have been estimated considering that the equipment involved was in their useful lives and therefore had constant failure rates. The main data sources used in the analysis were [9,10].

Frequencies of accidental scenarios involving human error were estimated considering the THERP technique [11] with the argument that this technique has been widely used in probabilistic safety analyses in nuclear power plants.

The incident and/or accident scenarios, selected by the preliminary hazard analysis as relevant, include cases in which the radioactive material would remain confined within the container tank during the incident and/or accident, while in others the release of radioactive material to the environment could occur.

In the incident and/or accident scenarios with release of radioactive material to the environment, it has been considered that there could be some kind of damage to the container tank. This damage could be caused by a vehicle rollover with the subsequent rupture of a line, or by a fire in the transfer vehicle. The fire would increase the container tank pressure, causing the rupture of pipes inside it. The release of radioactive material by air, by a radioactive cloud, or by water, could result in liquid radioactive waste from the container tank to flow to the plant rain drainage system and then to the sea located near the site. The waste liquid leaked in the accident could also remain near the vehicle, forming a pool and exposing the closest personnel to radiation.

The study sought to be the most comprehensive possible, considering all significant cases, especially in view of the radiation dose that would result for people in the plant vicinity, both for operators and for members of the public.

The radiological impact is expressed in terms of radiation dose. This dose results from calculations which are based on: *a*) theoretical models for calculating the dose used and recommended by entities that are internationally accepted, as the International Atomic Energy Agency (IAEA), which allow for evaluating the concentration of radioactive particles coming from radioactive sources and the exposure rate derived from it; *b*) specific radionuclide data for the most significant mechanisms contributing to dose, such as the dose coefficients for intake by inhalation of aerosols in the contaminated air and dose coefficients for adult members from the public through environmental contamination and exposure to air by immersion in a cloud recommended by the National Commission of Nuclear Energy [5]; *c*) consideration of design and operational parameters stipulated in the preparatory document for the transfer of liquid radioactive waste [1]; *d*) consideration of post-accident radioactive material dispersion pathways, conservative source term values and assumptions for the calculation of radiological impact [12].

The radiation doses calculated for the case of incident and/or accident scenarios were obtained according to the following approach: *a*) radiation dose to a worker due to radiation from a radioactive liquid pool [13]; *b*) radiation dose for a member of the public outside the Angra site due to the ingestion of seafood contaminated by radioactive material [14]; *c*) Radiation dose for a member of the public outside the Angra site due to the radioactive cloud [12]; *d*) Radiation dose for an employee due to incident and/or accident scenarios without the release of radioactive material into the environment [15].

According to Jones [16], the radiological risk of the *i*-th accident scenario, R_i, can be obtained as follows,

$$R_i = C_R.(f_i.D_i). \qquad (1)$$

where:
C_R = coefficient of radiological risk, [Sv^{-1}]. Its recommended value is 5×10^{-2} Sv^{-1} [17];
f_i = frequency of occurrence of the *i*-th accident scenario, [yr^{-1}];
D_i = effective dose associated with the *i*-th accident scenario, [Sv].

Eq. (1) applied to each individual scenario allows for obtaining its respective risk. It is used in order to determine the risk values for the incident and/or accident scenarios selected by criteria '*a*' and '*b*' of scenarios selection adopted in the PHA.

5. RESULTS OBTAINED

Using the criteria of scenarios selection "*a*" and "*b*" mentioned in the previous section, the 92 accident scenarios initially identified by the preliminary hazard analysis we have developed have been reduced to 58 [2].

The criterion mentioned in item *a* (Section 4) means that every accident scenario that has presented at least moderate severity in the preliminary hazard analysis should be evaluated for its effects (consequences). The criterion mentioned in item *b* (Section 4) recommends the estimation of radiation risk when the scenario has been classified as being of risk at least marginal. For the selected accident scenarios, frequencies, radiation dose, and radiation risks have been estimated using more elaborate models [2].

Among the incident and/or accident scenarios selected by the preliminary hazard analysis as relevant, some may lead to the release of radioactive material to the environment and others not. The incident and/or accident scenarios for which there is no release of radioactive material to the environment are those where the container tank transfer vehicle is unable to move by one of three transfer routes (due to, for example, lack of fuel, flat tire, mechanical failure, etc.), without affecting the container integrity.

By examining the accident scenarios for which the radiological risk was estimated, it was observed that the greatest risk of fatal cancer for a member of the public outside the Angra site is equal to 6.9 × 10^{-13} fatalities/yr. This risk refers to accident scenarios involving intrinsic failures (double-ended breaks) of valves, hoses, flanges, seals, gaskets and instrumentation lines, while filling the container tank in Angra 1 transfer area. This risk is approximately one million times lower than Eletrobras Termonuclear company target risk (10^{-6} casualties/yr) for such an operation. The higher frequency is also associated with this type of scenario, and it is equal to 1.4 × 10^{-6} yr^{-1} [2]. These results may be seen in Table 6, which displays the most relevant accidental scenarios from the point of view of their occurrence frequencies, dose or radiological risk. The branches shown refer to the filling station location in Angra 1 nuclear power plant and the three transfer routes considered in the analysis.

Table 6: Most relevant scenarios

Branch	Accidental scenario	Frequency (yr^{-1})	Dose (Sv)	Radiological Risk (yr^{-1})
Angra 1 filling station	A1-11	1.4E-06	9.85E-06	6.90E-13
	A1-12	3.5E-07	4.45E-06	7.79E-14
	A1-13	5.9E-08	9.85E-06	2.91E-14
	A1-14	1.5E-08	4.45E-06	3.34E-15
	A1-25	-(*)	1.17E-04	-
Transfer route # 1	R1-21	-	1.17E-04	-
	R1-22	-	1.17E-04	-
	R1-23	6.8E-08	5.07E-07	1.72E-15
	R1-24	6.8E-08	2.86E-06	9.72E-15
Transfer route # 2	R2-11	-	1.17E-04	-
	R2-12	2.7E-07	9.85E-06	1.33E-13
	R2-13	7.0E-08	4.45E-06	1.56E-14
	R2-14	-	1.17E-04	-
	R2-15	6.8E-08	5.07E-07	1.72E-15
	R2-16	6.8E-08	2.86E-06	9.72E-15
Transfer route # 3	R3-13	-	1.17E-04	-
	R3-14	2.7E-07	9.85E-06	1.33E-13
	R3-15	7.0E-08	4.45E-06	1.56E-14
	R3-17	6.8E-08	5.07E-07	1.72E-15
	R3-18	6.8E-08	2.86E-06	9.72E-15
	R3-19	6.8E-08	5.07E-07	1.72E-15

(*) negligible

It can also be seen from Table 6 that the accident scenario with the highest radiological impact on an individual outside the facility is caused by a major fire in the transfer vehicle, with the consequent release by a radioactive cloud of a large portion of the liquid radioactive waste within the full container tank. The radiation dose caused by this accident is equal to

117 μSv [2].

To allow for a broader perspective the risk curves for the Angra 1 filling station and for the three alternative routes to be used for the transportation of liquid radioactive waste from Angra 1 filling station to Angra 2 discharge station were estimated in this paper. As the resulting accidental scenarios for Angra 2 discharge station revealed that radiological risks were negligible (as compared to those of Angra 1 station and all three transfer routes), a radiological risk curve for it was not developed. The results were obtained considering Angra 1 filling station and each transfer route individually, and then the overall radiological risk curve. The coefficient of radiological risk was not used for estimating the radiological risk curves. Given an effect, in this case a radiation dose, in order to obtain the correct result one should multiply this dose by the coefficient given in Eq. (1) before reading the accident frequency in each radiological risk curve.

Figure 4 displays the radiological risk curve for Angra 1 filling station. Only 4 accidental scenarios were considered to generate it, so that the risk curve is not a smooth one. The reason for using 4 accidental scenarios only is that all other scenarios were neglected due to their small contribution. No logarithmic scales were used due to the limited variable ranges.

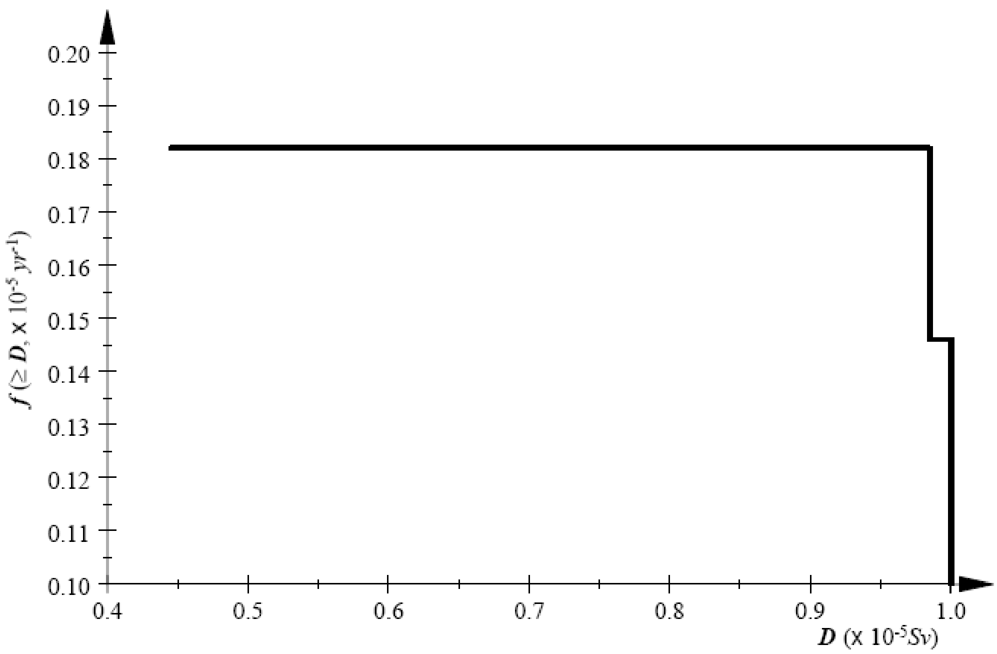


Figure 4: Radiological risk curve for Angra 1 filling station

The radiological risk curve shown in Figure 4 shows that the dose ranges approximately from $4x10^{-6}$ Sv to 10^{-5} Sv, with accident frequencies ranging from 10^{-6} /yr to 1.83×10^{-6} /yr.

There are three routes from Angra 1 filling station to Angra 2 discharging station [3]. Small branches in these routes are common, so that common accidental scenarios had to be removed, in order to be considered only once. Figure 5 shows the risk curve for route # 1.

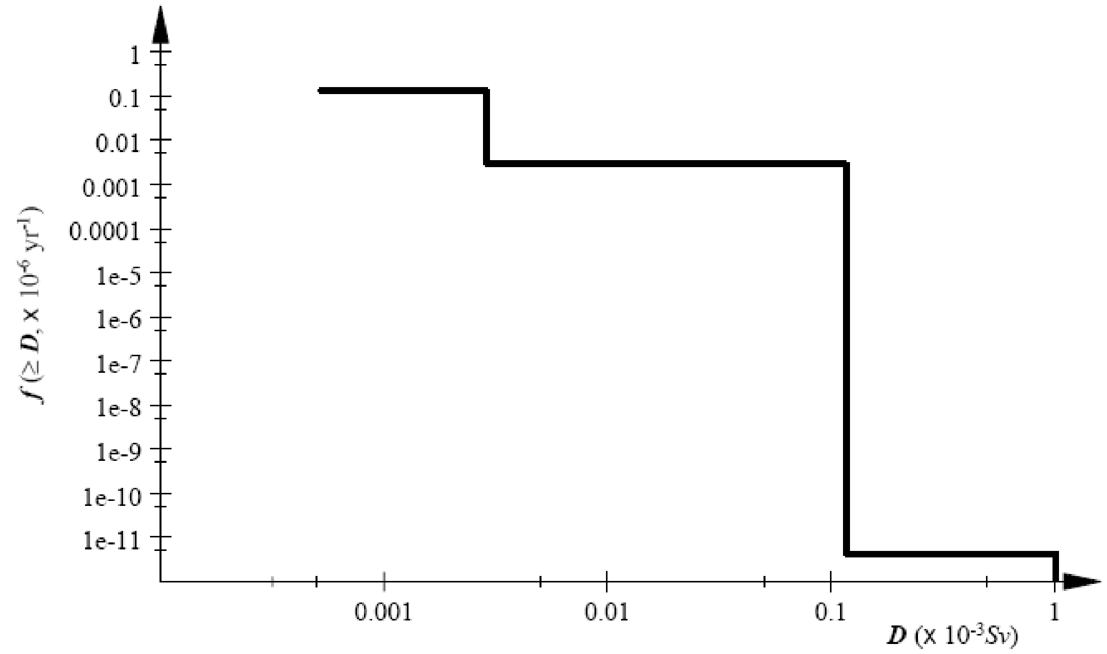


Figure 5: Radiological risk curve for Route # 1

For this case, logarithmic scales had to be used due to dose and frequency ranges. Doses range from $5x10^{-5}$ Sv to 10^{-3} Sv approximately, while accident frequencies vary from 10-18 /yr to 10-7/yr. In this case some accidental scenarios were preserved due to the doses estimated, based on the criteria discussed in Section 4.

Figure 6 displays the radiological risk curve for Route # 2. It may be seen that the dose range is similar to that of Route # 1, while accident frequencies range from 10^{-14} /yr to 5 x 10^{-7} /yr.

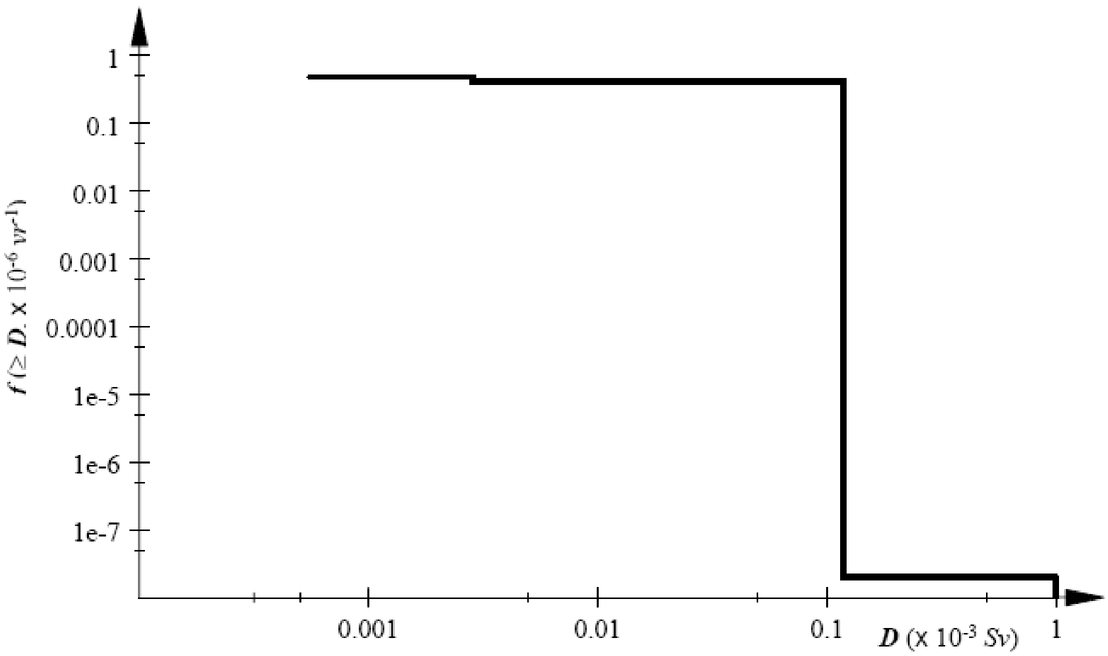


Figure 6: Radiological risk curve for Route # 2

Figure 7 displays the radiological risk curve for Route #3. Also for this case the dose range is similar to that for Routes # 1 and 2. As to the related accident frequency range, one may notice that the range for this route is the same as for Route # 2. The radiological risk curves for Routes # 2 and 3 are quite similar, because these routes have practically the same relevant characteristics for radiological risk evaluation.

The overall radiological risk curve is shown in Figure 8. In this case, all relevant accidental scenarios were taken into account and these scenarios were scanned for preventing double or triple counting, due to common route branches, as mentioned earlier. In this case, doses range from 5 x 10^{-7} Sv to 1.2 x 10^{-4} Sv approximately, while accident frequencies range from about 3 x 10^{-6} /yr to 4 x 10^{-14} /yr.

Considering the coefficient of radiological risk discussed in Section 4 in order to obtain radiological risk estimates, it may be seen that radiological risk ranges from about 3 x 10^{-15} /yr, that is, death risk due to radiation exposure, for the lowest accidental scenario up to about 7 x 10^{-13} /yr related to Angra 1 filling station. Considering Route # 1, this same range is from 3 x 10^{-25} /yr to 2 x 10^{-14} /yr. For Route # 2, this range comes to be from 4 x 10^{-26} /yr to about 10^{-13} /yr. The results for Route # 3 are 10^{-24} /yr up to 10^{-13} /yr. The overall risk ranges from 4 x 10^{-26} /yr to about 10^{-13} /yr.

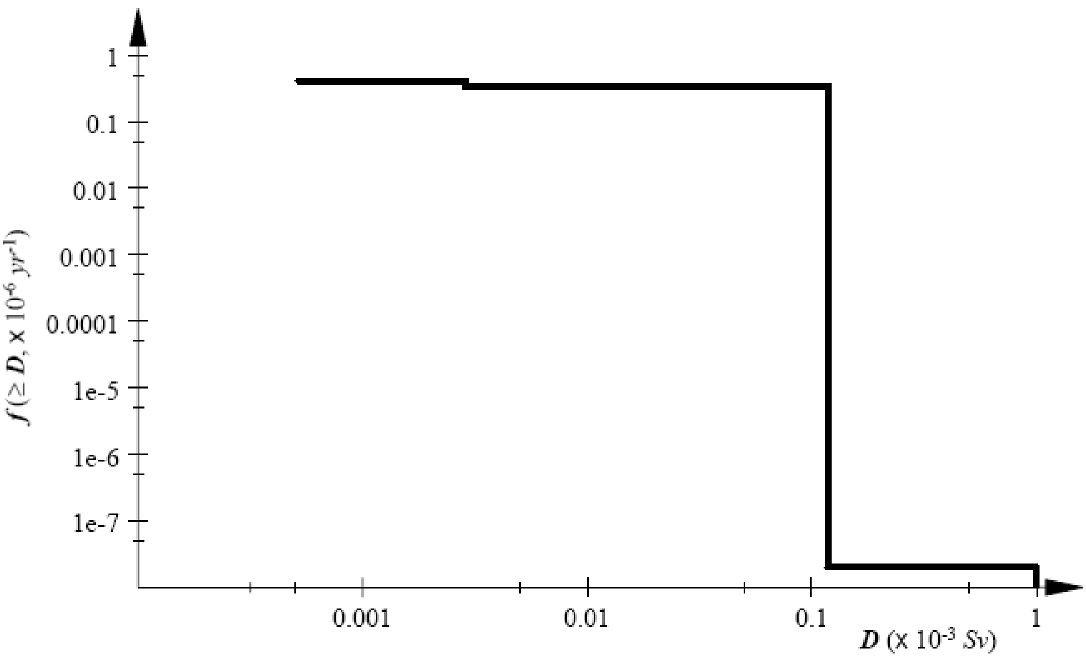


Figure 7: Radiological risk curve for Route # 3

The results presented show a great variability, but even considering this variability, no accidental scenario presents a significant radiological risk, as discussed earlier from the point risk estimate perspective. Of course many uncertainty sources can be identified, related both to parameter estimations and also epistemic uncertainty [19]. But it is quite reasonable to argue that even considering relevant uncertainty sources, risk curves as presented through a 95% percentile upper bound and a 5% percentile lower bound will not violate the radiological risk criterion adopted by Eletronuclear. Examples of these sources are failure and maintenance data scarcity and models for calculating different probabilities, as for example, that of fall of a transmission line.

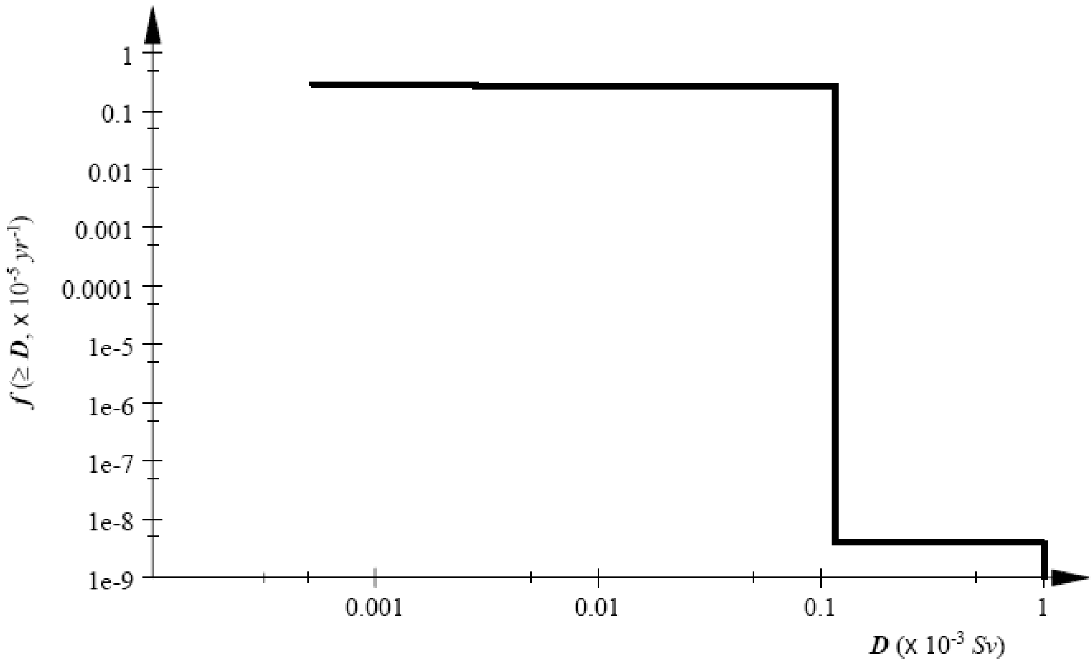


Figure 8: Radiological risk curve for the transfer operation from Angra 1 to Angra 2

6. CONCLUSIONS

The preliminary hazard analysis initially identified 92 incident and/or accident scenarios related to the transfer of liquid radioactive waste from Angra 1 to Angra 2 through a container-tank vehicle.

By considering in the preliminary hazard analysis a criterion for scenario selection that defines as representative those with at least marginal risk and moderate severity, the 92 accident scenarios initially identified have been reduced to 58, which demanded a more detailed evaluation. Of these, 29, by having at least marginal risk have been evaluated in detail in relation to their frequencies and doses, for the calculation of the radiological risk. The remaining 29 scenarios have been assessed in relation to their effects because they had at least moderate severity.

Among the scenarios selected by the preliminary hazard analysis there is no one involving the Angra 2 transfer area, which demonstrates the high safety degree of this station to perform the intended transfer operation.

The scenario that has the highest frequency is that involving the intrinsic failure (double-ended rupture) of valves, hoses, flanges, seals, gaskets and instrumentation lines, for the line branch used to connect the container tank to the Angra 1 transfer station (with the evaporator pump on), while filling the container tank. The frequency calculated for this scenario is equal to 1.4×10^{-6} yr^{-1}.

Radiological impact studies indicate that accident scenarios of higher severity can lead to an annual dose equal to 117 μSv to an individual of the public. These are accident scenarios with the occurrence of a fire in the transfer vehicle, causing the release by a radioactive cloud of approximately 20% of the total activity of the waste liquid in the initially full container tank.

Thus, it is observed that the largest radiological impact caused by the container tank in accident conditions corresponds to approximately 11.7% of the limit dose of 1 mSv per year set by the National Commission of Nuclear Energy standard [5] for an individual from the public.

Eletrobras Termonuclear adopts as an internal target a value of 10^{-6} casualties/yr for an operation transfer of this kind. The highest risk found for the accident scenarios analyzed was equal to 6.9×10^{-13} fatalities/yr, and also refers to the accident scenario with the highest calculated frequency, associated with intrinsic failures in Angra 1 transfer station. It should be noted that this risk is very low as compared to other activities, both voluntary and involuntary, involving industrial activities or not. A review of data of this nature can be found in [18]. The radiological risk of casualties found in this work is about 100 times lower than the fatality rate associated with the impact of meteorites on Earth's surface, for instance.

A radiological risk equal to 6.9×10^{-13} casualties/yr is equivalent to saying that one would expect the death of about seven people per year for each group of 10^{13} people who were affected by such a waste transfer, or the death of one person for every 1.43×10^{12} people per year affected by the same waste transfer. Thus, it can be stated that the transfer of liquid radioactive waste from Angra 1 to Angra 2 by a container tank is very safe. Still, a set of recommendations (e.g., preparation and/or improvement of procedures for carrying out the various stages of the liquid waste transfer) has been recommended, whose main objective is to meet the ALARA principle [3].

When one considers the radiological risk curves displayed in this paper it can be seen that the risk range is of about 13 orders of magnitude. This variability is due to different accident scenarios for which different hypothesis had to be made in order to make realistic estimates. But even considering the variability of many input parameters and also epistemic uncertainty, the results show that from the point of view of risk curves, this design modification can be licensed.

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